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INFLUENCE OF MAGNETIC SHEAR ON THE CURRENT CONVECTIVE INSTABILITY--ETC(U)

APR 80 J D HUBA, S L OSSAKOW

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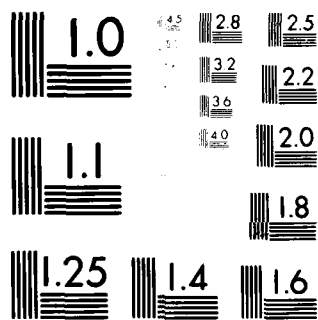
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# INFLUENCE OF MAGNETIC SHEAR ON THE CURRENT CONVECTIVE INSTABILITY IN THE DIFFUSE AURORA

## I. INTRODUCTION

Recently, the current convective instability has been suggested as a mechanism to explain the scintillation enhancements observed by the DNA Wideband satellite in the high latitude diffuse aurora F region (Ossakow and Chaturvedi, 1979). These enhancements are presumably due to field aligned, sheet-like ionospheric irregularities (Rino et al., 1978) generated by the instability. Associated with the enhancements are a density gradient in the north-south total electron content (TEC) and a weak magnetic field aligned current due to precipitating auroral electrons (Fremouw et al., 1977; Rino et al., 1978); both of these features are necessary to excite the current convective instability (Kadomtsev, 1965). Also, the dominant modes appear to be in the north-south direction, i.e., parallel to the density gradient (Rino et al., 1979). This is contrary to the linear theory of the instability which indicates the most unstable waves are perpendicular to both the ambient magnetic field and the density gradient. However, Chaturvedi and Ossakow (1979) have proposed a nonlinear mode coupling mechanism which stabilizes the instability and nonlinearly generates waves parallel to the density gradient, in accordance with observations.

In this paper we discuss the influence of magnetic shear on the current convective instability and its role in the diffuse aurora. Magnetic shear can dramatically affect an instability as witnessed by the controversy over its role in the universal drift instability (Ross and Mahajan, 1978; Tsang et al., 1978). The primary action of shear is to allow the mode to sample a range of  $k_{\parallel}$  in the localization region

(Mikhailovskii, 1974). If the mode is sensitive to  $k_{\parallel}$ , as is the current convective instability, then shear can have a strong influence on the instability (generally, stabilizing and localizing). The magnetic shear in the auroral region is produced by the weak field aligned current and its scale length can be estimated from  $(\nabla \times \underline{B}_0)_{\parallel} = (4\pi/c)J_{0\parallel}$ . We define the scale length for shear as  $L_s = (c/4\pi)B_{0\parallel}/J_{0\parallel}$  (Mikhailovskii, 1974) and using  $B_{0\parallel} \approx 0.5$  G and  $J_{0\parallel} \approx 8\mu$  amps/m<sup>2</sup> (Ossakow and Chaturvedi, 1979) we find that  $L_s \sim 5000$  km. Since the density gradient scale length ( $L_n = (d \ln n_0/dy)^{-1}$ ) is  $L_n \sim 10-100$  km we obtain  $L_s/L_n \sim 50-500$ . Thus, a weak magnetic shear can exist in the diffuse auroral region. However, since the current convective modes are predominantly field aligned (i.e.,  $k_{\parallel} \ll k_{\perp}$ ), even a weak magnetic shear can have an important influence on them. The two major results of our calculation are that magnetic shear (1) reduces the growth rate of the current convective instability, and (2) strongly localizes the mode in the north-south direction.

## II. THEORY

The physical configuration we consider is described as follows. The ambient magnetic field is  $\underline{B} = B_0 \hat{e}_z + B_{ox}(y) \hat{e}_x$  where  $B_{ox}$  is produced by  $J_{0\parallel}$  and  $B_0 \gg B_{ox}$ . The density varies in the y direction (north-south) and a field aligned current exists  $\underline{J}_{0\parallel} = J_{0\parallel} \hat{e}_z$ . Following Ossakow and Chaturvedi (1979), the basic set of equations we use is

$$\frac{\partial n_a}{\partial t} + \nabla \cdot (n_a \underline{V}_a) = 0 \quad (1)$$

$$\nabla \cdot \tilde{\mathbf{J}} = 0; \quad \tilde{\mathbf{J}} = \sum_{\alpha} e_{\alpha} n_{\alpha} \tilde{\mathbf{v}}_{\alpha} \quad (2)$$

$$\tilde{\mathbf{v}}_i = \frac{c}{B_0} \tilde{\mathbf{E}} \times \hat{\mathbf{e}}_z + \frac{c}{B_0} \frac{\nu_i}{\Omega_i} \tilde{\mathbf{E}}_{\perp} + \frac{c}{B_0} \frac{\Omega_i}{\nu_i} \tilde{\mathbf{E}}_{\parallel} + \tilde{v}_{i0\parallel} \quad (3)$$

$$\tilde{\mathbf{v}}_e = \frac{c}{B_0} \tilde{\mathbf{E}} \times \hat{\mathbf{e}}_z - \frac{c}{B_0} \frac{\Omega_e}{\nu_e} \tilde{\mathbf{E}}_{\parallel} \quad (4)$$

where  $\alpha$  denotes the species (e: electrons, i: ions),  $n$  is the density,  $\tilde{\mathbf{v}}$  is the velocity,  $\nu$  is the collision frequency,  $e$  is the charge.

$\Omega_{\alpha} = |e_{\alpha}| B_0 / m_{\alpha} c$ ,  $\tilde{\mathbf{J}}$  is the current and  $\tilde{v}_{i0\parallel}$  is the diffuse auroral precipitation velocity along  $\tilde{\mathbf{B}}$ . Note that  $\tilde{v}_{d\parallel} = \tilde{v}_{i0\parallel} - \tilde{v}_{e0\parallel}$  and we have chosen a reference frame such that  $\tilde{v}_{e0\parallel} = 0$ . We neglect inertial and temperature effects, and the electron Pedersen drift compared to the ion Pedersen drift. In Eqs. (3) and (4) we assume  $\nu_i$  represents ion-neutral collisions and  $\nu_e$  represents electron-ion collisions.

Equations (1) - (4) are valid in the high latitude F region where

$$\nu_{\alpha} / \Omega_{\alpha} \ll 1.$$

We linearize Eqs. (1) - (4) using  $n = n_0(y) + \delta n$ ,  $\tilde{\mathbf{E}} = -\nabla \delta \phi$ ,  $\tilde{\mathbf{v}} = \tilde{\mathbf{v}}_0 + \delta \tilde{\mathbf{v}}$  and assume perturbed quantities vary as  $\exp[i(k_x x + k_y y + k_z z - \omega t)]$ . Making use of quasineutrality, we find from the electron continuity equation and  $\nabla \cdot \delta \tilde{\mathbf{J}} = 0$  that

$$\left[ \frac{k_z v_d}{\omega} \left( i k_x \epsilon_n - \frac{\Omega_e}{\nu_e} k_z^2 \right) + \frac{\nu_i}{\Omega_i} (k_x^2 + k_y^2) + k_z^2 \left( \frac{\Omega_i}{\nu_i} + \frac{\Omega_e}{\nu_e} \right) \right] \delta \phi = 0 \quad (5)$$

where  $v_d = v_{i0\parallel} - v_{e0\parallel} = v_{i0\parallel}$ ,  $\epsilon_n = d \ln n_0 / dy$  and we have assumed  $\epsilon_n \ll k_y$ . Note that the local dispersion equation is recovered by setting the bracketed quantity in Eq. (5) equal to zero (using  $k_y = 0$ ).



We can obtain a differential equation for  $\delta\phi$  which describes the non-local mode structure, including the effect of magnetic shear, by making the following identifications (Mikhailovskii, 1972)

$$k_y^2 = -\partial^2/\partial y^2; k_z = k_x(y/L_s)$$

We find that

$$\frac{\partial^2 \delta\phi}{\partial y^2} - k_x^2 Q(\omega, k_x, y) \delta\phi = 0 \quad (6)$$

where

$$Q = 1 + \frac{y^2}{L_s^2} \frac{\Omega_i}{v_i} \left( \frac{\Omega_i}{v_i} + \frac{\Omega_e}{v_e} \right) + \frac{k_x v_d}{\omega} \frac{y}{L_s} \frac{\Omega_i}{v_i} \left[ 1 - \frac{\epsilon_n}{k_x} - \frac{\Omega_e}{v_e} \frac{y^2}{L_s^2} \right] \quad (7)$$

Since the mode is almost purely growing ( $\omega_r \ll \gamma$  where  $\omega = \omega_r + i\gamma$ ),

we can approximate Q by

$$Q_R = 1 + \frac{y^2}{L_s^2} \frac{\Omega_i}{v_i} \left( \frac{\Omega_i}{v_i} + \frac{\Omega_e}{v_e} \right) + \frac{k_x v_d}{\gamma} \frac{y}{L_s} \frac{\Omega_i}{v_i} \frac{\epsilon_n}{k_x} \quad (8)$$

$$Q_I = \frac{k_x v_d}{\gamma} \frac{\Omega_i}{v_i} \frac{\Omega_e}{v_e} \frac{y^3}{L_s^3} \quad (9)$$

where  $Q = Q_R + iQ_I$ . For the parameters of interest we note that

$Q_I \ll Q_R$  (to be justified a posteriori)

We now let  $\tilde{y} = y/L_n$  and  $\tilde{L}_s = L_s/L_n$  where  $L_n = 1/\epsilon_n = (d \ln n_0/dy)^{-1}$

and rewrite Eq. (6) as

$$A \frac{\partial^2 \delta\phi}{\partial \tilde{y}^2} + [B - C(\tilde{y} - \tilde{y}_M)^2] \delta\phi = 0 \quad (10)$$

where

$$A = 1/k_x^2 L_n^2$$

$$B = \frac{1}{4} \left( \frac{\epsilon_n v_d}{\gamma} \right)^2 \left( 1 + \frac{v_i \Omega_e}{v_e \Omega_i} \right)^{-1}$$

$$C = \frac{\Omega_i}{v_i} \left( \frac{\Omega_i}{v_i} + \frac{\Omega_e}{v_e} \right) \frac{1}{\ell_s^2}$$

$$\tilde{y}_M = - \frac{\ell_s}{2} \frac{\epsilon_n v_d}{\gamma} \left( \frac{\Omega_i}{v_i} + \frac{\Omega_e}{v_e} \right)^{-1}$$

Here,  $\tilde{y}_M$  is the position of the minimum in the potential well  $Q$ .

Equation (10) is in the form of Weber's equation and the eigenfrequency is defined by

$$B = (2m + 1)(AC)^{\frac{1}{2}} \quad (11)$$

where  $m$  is the mode number (i.e.,  $m = 0, 1, 2, \dots$ ). Thus the growth rate of the current convective instability, including the effect of magnetic shear, is found to be

$$\gamma = \gamma_M^L / (1 + (2m + 1)\Delta_s)^{\frac{1}{2}} \quad (12)$$

where

$$\gamma_M^L = \frac{1}{2} \epsilon_n v_d \left( 1 + \frac{v_i \Omega_e}{v_e \Omega_i} \right)^{-\frac{1}{2}} \quad (13)$$

$$\Delta_s = \left[ \frac{\Omega_i}{v_i} \left( \frac{\Omega_i}{v_i} + \frac{\Omega_e}{v_e} \right) \right]^{\frac{1}{2}} (1/\ell_s k_x L_n). \quad (14)$$

Note, in the limit  $\ell_s \rightarrow \infty$  (i.e., no shear) that  $\Delta_s \rightarrow 0$  and Eq. (12) reduces to the expression obtained by Ossakow and Chaturvedi (1979)

for the maximum growth rate based upon local theory. Also, we find that the effective  $k_z$  associated with the fundamental mode ( $m=0$ ) to be

$$k_z^{\text{eff}} = k_x (y_M / \ell_s) = - k_{zM}^L (1 + \Delta_s)^{1/2} \quad (16)$$

where

$$k_{zM}^L = k_x \left[ \frac{\Omega_i}{v_i} \left( \frac{\Omega_i}{v_i} + \frac{\Omega_e}{v_e} \right) \right]^{-1/2} \quad (17)$$

is the value of  $k_z$  for the maximum growing mode from local theory.

Moreover, the fundamental mode is localized about

$$\tilde{y}_M = - \ell_s \left[ \frac{\Omega_i}{v_i} \left( \frac{\Omega_i}{v_i} + \frac{\Omega_e}{v_e} \right) \right]^{-1/2} (1 + \Delta_s)^{1/2} \quad (18)$$

within a region

$$\tilde{y}_{tp} = \tilde{y}_M \pm \left\{ \frac{\ell_s^2}{k_x^2 L_n^2} \left[ \frac{\Omega_i}{v_i} \left( \frac{\Omega_i}{v_i} + \frac{\Omega_e}{v_e} \right) \right]^{-1} \right\}^{1/2}. \quad (19)$$

### III. DISCUSSION

We now apply our results for typical ionospheric conditions during the diffuse aurora to assess the influence of magnetic shear on the current convective instability. We choose  $L_n \approx 50$  km,  $L_s \approx 3000$  km,  $v_i / \Omega_i = v_e / \Omega_e = 10^{-4}$ ,  $k_x \approx 1$  km $^{-1}$  and  $v_d \approx 500$  m/sec. We find that the growth rate of the fundamental mode is  $\gamma \approx 2 \times 10^{-3}$  sec $^{-1}$  which is a factor of 2 smaller than that obtained from shearless local theory. Higher order modes have somewhat lower growth rates. Thus, although the growth rate has been reduced by shear effects, it is still sufficiently large to account for the observed scintillation enhancements. The mode is localized in the north-south direction within a region  $\Delta y \approx 2 \times 10^{-2} L_n \approx 1.0$  km. Moreover, if we define an effective  $k_y$  as

$k_y^{\text{eff}} \approx 2\pi/\Delta y$  we obtain  $k_y^{\text{eff}} \approx 6 \text{ km}^{-1} > k_x$ . This result indicates the strong two dimensional structure of the mode in the plane perpendicular to the magnetic field during the linear phase of the instability.

Finally, several aspects of the present analysis deserve mention. First, we have neglected the ambient electric field  $\underline{E}_0$  which is generally directed west or northwest in the diffuse aurora. (Note that the plasma is stable to the standard  $\underline{E} \times \underline{B}$  drift instability). This assumption is valid in the limit  $|k_z V_d| \gg (k_x c E_0 / B_0) v_i / \Omega_i$  which is satisfied for  $k_z \approx k_z^{\text{eff}}$ . However, because  $k_z$  varies in the  $y$  direction, it is possible that this condition breaks down in part of the mode localization region. Moreover, for the geometry under consideration,  $\underline{E}_0$  is a stabilizing effect and we anticipate that including  $\underline{E}_0$  in the theory will reduce the growth rate slightly (Eq. (12)) and skew the mode structure of the eigenfunctions. We will discuss this effect in more detail in a later publication. Secondly, we have ignored the spatial dependence of the density and considered mode localization only due to shear. We have investigated the nonlocal behavior of the current convective instability for a density profile  $n(y) = n_0 + \Delta n \tanh(y/\lambda)$  (with  $\Delta n \sim n_0/2$ ) in a shearless magnetic field. We find that the eigenmodes are localized in a region  $\Delta y \gtrsim \lambda/4 \approx L_n/4$  and that the fundamental eigenfrequency agrees well with the local theory. Thus, for ionospheric conditions in the diffuse aurora, the mode structure is determined by magnetic shear and the neglect of the spatial dependence of density is justified. And finally, inertia and diffusion damping should be considered in a more comprehensive analysis. Again, we defer a discussion of these effects to a future report.

#### IV. SUMMARY

In conclusion, we have considered the influence of magnetic shear on the current convective instability for conditions typical of the high latitude F region during the diffuse aurora. We find that magnetic shear (1) reduces the growth rate of the instability from its value based upon shearless, local theory and (2) substantially localizes the mode structure in the north-south direction. This final result indicates that the mode structure is two dimensional in the plane perpendicular to the magnetic field during the linear phase of the instability. However, since the scintillation enhancements occur over a region  $\geq 100$  km in the north-south direction (Rino et al., 1978) a nonlinear mechanism is required to spread or convect the shear localized turbulence over this much larger region.

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